

Chapter 6. Single-Electron Spectroscopy

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6.1 Goals and Objectives

Three years ago, we developed single-electron capacitance spectroscopy (SECS). This is a technique for measuring the quantum energy levels of nanoscale objects such as quantum dots, single impurity atoms, and localized electronic states in a semiconductor. The resolution of the method is limited only by the sample temperature, and objects containing as few as one electron may be probed. We intend to develop this type of single-electron spectroscopy into a general tool for studying nanostructured materials.

In the simplest version of SECS, we position the small object of interest between the two plates of a "tunnel capacitor". Electrons may tunnel between the object and the "bottom" plate, while a large barrier forbids tunneling to the "top" plate. By adjusting the voltage applied across the plates, single electrons are caused to tunnel onto and off the object. Once the electron tunnels onto the object, image charge is induced onto the top plate. By building a high electron mobility transistor (HEMT) directly onto the "chip" containing the sample, we demonstrated that we could detect and precisely measure this image charge.

In addition to applying a DC bias across the tunnel capacitor, we prompt single electrons to tunnel back and forth between the object and the bottom plate using an AC voltage. We then synchronously detect signals due to electronic tunneling. Peaks appear in the response at those particular positions in DC bias at which a quantum state in the object is

energy resonant with the chemical potential in the bottom plate. A simple geometric scale factor converts the DC bias scale into an energy scale for the object to allow a quantitative energy level spectroscopy. In essence, we measure the ground state energy levels of a system containing a specifiable number N of electrons as a function of an extrinsic parameter (e.g., magnetic field). The resolution of this technique is limited only by the sample temperature (typically 300 mK).

We are developing SECS into a tool for the characterization of many types of electronic structures. We have used it to measure spectra from *single* impurity atoms and a wide variety of traps. Now we are enhancing the technique by: (1) increasing its frequency response so that times for electrons to occupy and leave single traps can be characterized over a wide range; (2) adding a scanning capability so that the precise positions, shapes, and sizes of traps may be identified along with the determination of their energy spectra; and (3) creating more sensitive detectors in order to characterize samples much more rapidly.

Since the arrival of Professor Ashoori at MIT in 1993, much of our work has been directed largely toward the setup of our low temperature laboratory and developing tools for sample preparation. In this regard, we have completed installation of a top-loading dilution refrigerator with a 16 Tesla integral magnet, a helium-3 refrigerator, an electron beam lithography system, and a scanning tunneling microscope controller.

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6.2 Traps Created by Disorder and Impurities in Semiconductor Structures

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Ho Bun Chan, David Berman, Professor Raymond C. Ashoori

One system that we have studied in detail is a circular disk of electrons 1 mm in diameter and contained within a GaAs quantum well. We empty this disk and begin adding electrons to it. The first few electrons enter localized states of this disk. Observation of the magnetic field evolution of these energy levels allows a characterization of the type of minimum which localizes the electron as well as the lateral extent (localization length) of quantum levels. We find that some of the states are localized on minima of the disorder potential while others are located on *single* impurity atoms. At higher filling, the sample behaves as a disk of two-dimensional electron gas (2DEG), with Landau level structure evident in magnetic field.

We intend to exploit samples of this type as a laboratory to study systems of localized electrons, and much work remains. For instance, although the first electrons in the disk are in spatially separate localized states, they interact electro-statically. These interactions create correlations between the electron additions that are of principal interest in studying the Coulomb gap. Our experiment can thus directly measure the density of states within the Coulomb gap. As the disk is filled, near the metal-insulator transition these correlations should evolve into the Coulomb blockade with nearly periodic electron additions in gate bias. Our ability to monitor this evolution together with direct measurements of the localization length of quantum states will provide an unprecedented view of the metal-insulator transition. Although all electronic states in two-dimensions are thought to be localized, the localization length increases smoothly with chemical potential. The sample displays metallic conduction when the localization length grows to become equal to the sample size. In magnetic field, this picture changes radically with the localization length of electronic states thought to oscillate as the chemical potential is swept through the Landau level

structure. This picture is central to theories of the quantum Hall effect. Our direct probe of localization lengths of electronic states can provide a key test of these ideas.

6.3 Artificial Atoms

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We have created another sample in which electrons accumulate at a single potential minimum defined by gating. This sample behaves as a true "quantum dot" or an artificial atom. We have measured the ground state energies of this system in magnetic field with electronic population from 0-50. The most apparent new physics arises with only two electrons in the dot. We observe an exchange induced singlet-triplet crossing of the two-electron state as the magnetic field is increased beyond 1.5 Tesla. This is the first instance in which a two-electron singlet-triplet crossing has been observed; for He atoms it takes place at fields of $>400,000$ Tesla. Understanding our results for a dot containing three or more electrons becomes quite complicated, requiring intensive computer modeling. However, with more than 10 electrons the system begins to approximate a very small 2DEG. Features, related to the quantum Hall effect, arise when the dot encloses integer numbers of electrons per flux quantum threading the dot. At higher fields, we see features suggestive of the fractional quantum Hall effect in both the energetics and tunneling rates of electrons.

A central topic in quantum dot physics is the role of the electron-electron interaction in modifying a dot's electronic level structure. Single-particle-like states exist in the limit of very small dots, while level structure is dominated by the electron-electron interaction in larger dots. Since the confinement potential in semiconductor quantum dots can be controlled at will, there exists a continuum of physics that we may explore. We plan a detailed examination of quantum dots in different size regimes.

6.4 Spatially Resolved Charge Sensing

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We are presently developing methods for adding spatial resolution to our charge sensitive measurements. We are constructing a charge sensitive scanning tunneling microscope (STM) for low temperature studies.

As a first step, we have recently completed building a room temperature STM. This STM is a "walker" design. Its chief advantages are that it allows large lateral range of motion in observations of the surface of a sample, and no mechanical linkages to the sample are required. Figure 1 presents room temperature data of a gold $\langle 111 \rangle$ surface. The lateral dimensions are 100 Angstroms, and the observed steps are about 50 Angstroms high.

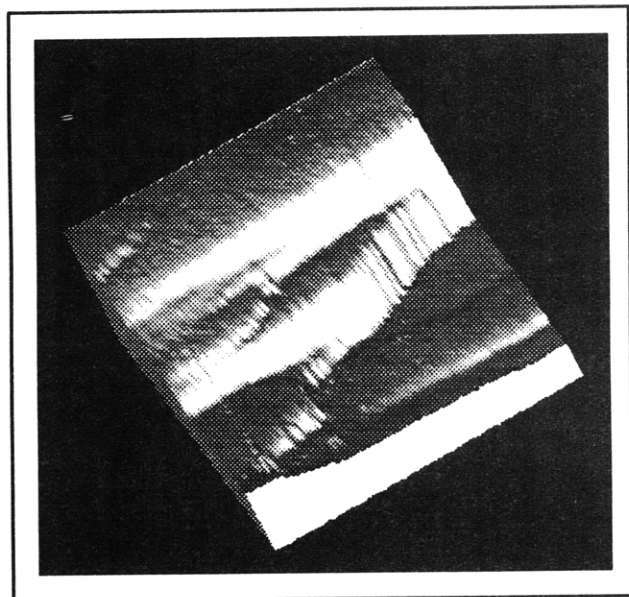


Figure 1. Scanning tunneling microscope image of a Au $\langle 111 \rangle$ surface taken with our home-built scanning tunneling microscope. The lateral dimensions are 100 Angstroms, and the terraces are 50 Angstroms tall.

We are presently constructing a low temperature STM. It will operate inside our helium-3 refrigerator at a temperature of 0.3 K.

6.5 Single-Electron Transistors for Spectroscopy

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We are developing single-electron transistors to improve the sensitivity of SECS. Invented about five years ago, much interest has been focused on the study of the physics of the devices themselves. With further development, these transistors hold promise for being the most sensitive electrometers available. Calculations indicate that they could provide one or two more orders of magnitude improvement in charge sensitivity over our present HEMTs. Such sensitivity will greatly enhance SECS and will make feasible a number of experiments that are presently impractical.

We have converted an existing JEOL 6400 scanning electron microscope for use in electron beam writing. Using this system and the processing facilities of the Center for Materials Science and Engineering, we have recently created our first single-electron transistors fabricated from aluminum and aluminum oxide. We are presently attempting to integrate these devices onto semiconductor structures.

6.6 Publication

Ashoori, R.C., H.L. Stormer, J.S. Weiner, L.N. Pfeiffer, K.W. Baldwin, and K.W. West. "Energy Levels of an Artificial Atom Probed with Single-Electron Capacitance Spectroscopy." *Surf. Sci.* 305: 558-565 (1994).

